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1. INTRODUCTION

On-pad launch vehicle wind induced translation and structural response are the subject of engineering design analyses and operational planning. The NASA ARES-1 may have to be constrained, to prevent contact with pad infrastructure, to reduce loads and to insure that the projected on-pad exposure period is within the estimated fatigue life of attachments to the launch pad. The ARES-1 solid rocket booster (SRB) needs to be protected from extreme loads because its re-usable base (the "aft-skirt") is attached to the launch pad. Detailed engineering analysis of launch vehicle wind induced translation, structural loads and fatigue life require a detailed definition of wind forcing functions at locations along the vehicle. Kennedy Space Center (KSC) near-pad wind measurements at 18.3m elevation are below the elevation of the base of on-pad Shuttle and ARES launch vehicles. The near-pad wind measurement system currently sampled at 1/sec has an effective frequency response that begins to roll-off at frequencies less than the nominal maximum frequency of 0.5Hz. This does not satisfy the need for engineering analysis to define wind forcing functions to at least 5 Hz.

The power spectrum density (PSD) model (Fichtl and McVehil, 1970) that is an essential component of the simulation process described herein is based on wind measured at five elevations on the KSC 150-m meteorological Tower 313. The wind data sampled at 10/sec are from relatively light cup anemometers more suitable for turbulence research and PSD modeling compared to current sensors that have reduced frequency response, but have the capability needed for long-term exposure for range support of Shuttle launches.

The methodology for application of PSD and coherence models described in this paper permits simulation of wind time series at any desired location on launch vehicles for a user selected frequency range suitable for engineering design applications. Although this paper describes a process that does not require measurements to simulate wind, the process can be adapted to simulate wind along the launch vehicle, given a measured wind at 18.3m. This is the subject of ongoing work.

2. BACKGROUND

Ground wind time series are simulated based on PSD model for the longitudinal and lateral components of turbulence and a coherence model for the reduction of correlation between wind components at two locations as a function of temporal frequency, wind speed and distance between locations (Anon, 2000). Short distances reduce correlation only at high frequencies; as distances increase correlation is reduced over a wider range of frequencies. The longitudinal component is oriented in the direction of the mean wind; the lateral component is perpendicular to the direction of the mean wind.

Current applications of simulated ground winds time series

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include:

- ARES launch vehicle solid rocket booster aft-skirt wind induced loads and structural fatigue life assessment
- ARES on-pad response to wind (vortex shedding) and development of a restraint system/vibration damper
 - Time series generated will be at mean wind speeds that bound the wind speed that produces vortex shedding at the frequencies of the primary response modes of the on-pad vehicle
- Establishment of ARES launch vehicles ascent guidance system initialization uncertainty caused by wind induced structural response
 - The vibration (translation and angular) response (to wind) is evaluated at the navigation sensor location inside the avionics ring of the launch vehicle
 - Wind gust excitation is to be input to a structural model
 - Longitudinal and lateral wind component time series are simulated at locations on the ARES launch vehicle

3. GROUND WIND PSD MODEL FOR ATMOSPHERIC TURBULENCE

The PSD model (Eq.1) for ground wind turbulence was developed for engineering applications (Fichtl and McVehil, 1970) from horizontal wind measurements at the NASA 150-m meteorological tower at Cape Canaveral, FL. The model is specified in Shuttle design documentation (Anon, 1999 and in somewhat different form in Anon, 2000).

$$\text{psd}_{k, kk} := \frac{d1 \cdot \left(\frac{x_{kk}}{18.3} \right)^{d3} x_{kk} \frac{\text{um183}^2}{u_{x_{kk}}}}{\left[1 + d2 \cdot \left[\left(\frac{18.3}{x_{kk}} \right)^{d5} \cdot \frac{n_k \cdot x_{kk}}{u_{x_{kk}}} \right]^{d6} \right]^{d4}} \quad (1)$$

Where,

psd = power spectrum density, (m²/s²)/1/sec

d1, d2, d3, d4, d5, d6 are non-dimensional constants for the longitudinal and lateral components of turbulence

x = elevation (m)

um183 (m/sec) = mean wind speed at 18.3m elevation

ux = mean wind speed (m/sec) at x

n = temporal frequency (1/sec)

k = index for frequency variable

kk = index for selected variable and related variables, in this case ux calculated from um183 and x

The PSD model and the mean of 20 simulations are illustrated in Fig. 1. As the number of simulations increase the deviations of the mean from the model decreases.

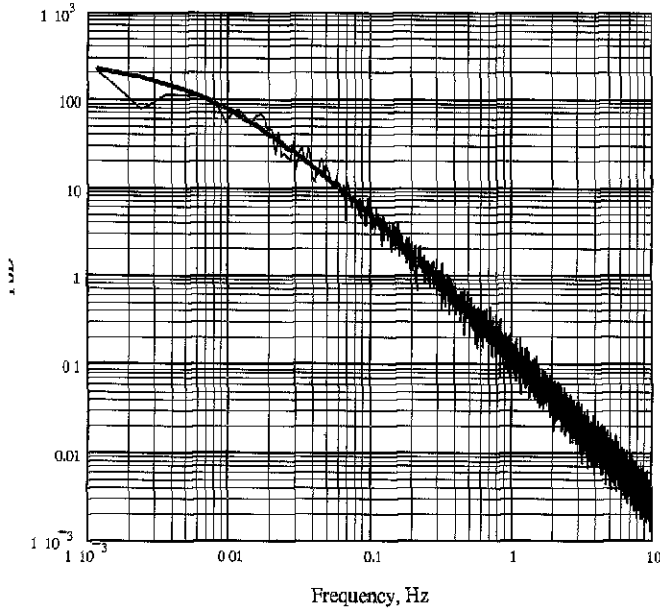


Fig.1 Mean PSD (perturbed) of the 20 Simulated Series Versus the PSD Model (smooth) at elevation 102.5 m and mean wind speed 9.871 m/s

4. BASIC ELEMENTS OF WIND SIMULATION AT ELEVATION X AND MEAN WIND SPEED U_X

- Selection of the frequency range for the application and the simulated wind time series
- Integration of the PSD to obtain the variance and standard deviation (SDPSD) of the time series to be simulated
- Generation of n-values of Gaussian distributed white noise with zero mean and SD = 1; "n" is chosen such that the fast Fourier transform (FFT) is at the same frequencies defined for the PSD model
- Calculation of the FFT of the Gaussian series (FFTGA)
- Low-pass filtering of FFTGA by multiplying each Fourier component of FFTGA by the square-root of the normalized PSD
- Calculation of the un-adjusted simulated time series, S, which is the inverse transform of the low-pass filtered FFTGA
- Calculation of the adjusted simulated time series SA such that it has the standard deviation calculated from the PSD model, i.e.
 $SA = S * SDPSD/SDS$

5. SIMULATION PROCESS FOR CONCURRENT WIND COMPONENT TIME SERIES AT SELECTED LOCATIONS

Simulation of a wind component at the nearest adjacent location (and all other succeeding next nearest locations) is based on a coherence model (Anon., 2000) for the coherence decay between winds at two locations as a function of temporal frequency f , and distance, d , (Eqs.2 and 3); where the adjacent locations are displaced vertically or horizontally.

For vertical separation, the coherence squared is,

$$\text{coh}_k^2 = \exp \left(-0.693 f_k \frac{\frac{x_2}{u_{x_2}} - \frac{x_2 - d}{u_{x_2 - d}}}{0.036} \right) \quad (2)$$

Where, u_{x_2} and $u_{x_2 - d}$ are the mean wind speeds (m/s) at adjacent locations along the vertical x-axis and d is the vertical distance between adjacent nodes.

For horizontal separation, the coherence squared becomes,

$$\text{coh}_k^2 = \exp \left(-0.693 f_k \frac{d}{u_x (0.036)} \right) \quad (3)$$

Where, d is the absolute value of the y coordinate difference (m) between the two locations at elevation x . An example is illustrated Fig.2.

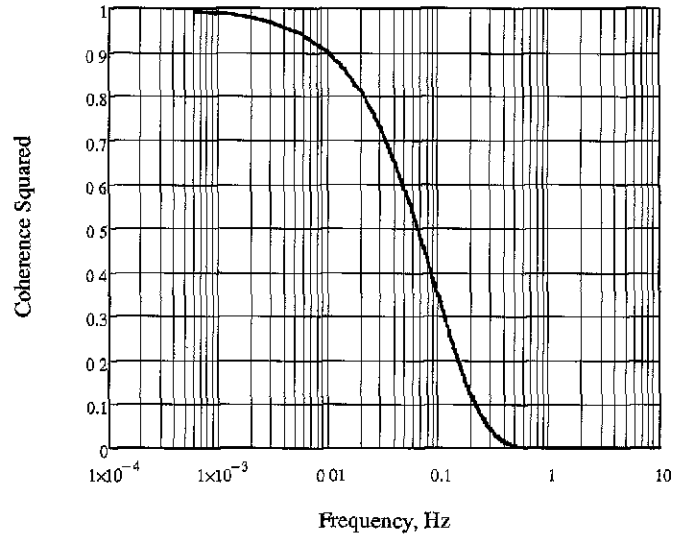


Fig 2. Coherence squared (Eq.2) for $d=5.5$ m at elevation 102.5 m and mean wind speed 9.871 m/s

- The coherence function is used to model the Fourier components A_k^* and B_k^* of the wind at a selected location, given the Fourier components A_k and B_k of the simulated time series at an adjacent location and another set of essentially uncorrelated Fourier components AA_k and BB_k calculated at the selected location. The coherence weighted Fourier components at the selected location are:

$$A_k^* = \text{coh}_k A_k + \sqrt{1 - \text{coh}_k^2} AA_k \quad (4)$$

$$B_k^* = \text{coh}_k B_k + \sqrt{1 - \text{coh}_k^2} BB_k \quad (5)$$

The coherence weighted FFT, cohFFT is

$$\text{cohFFT}_k = A_k^* + B_k^* i \quad (6)$$

The coherence weighting in Eqs.4 and 5 is analogous to the correlation weighting used to derive a correlated

Gaussian distributed data base G3 from uncorrelated Gaussian distributed data bases G1 and G2 with zero mean and standard deviation X, where the target correlation between G3 and G1 is C.

$$G3 = G1 * C + G2 * \sqrt{1 - C^2} \quad (7)$$

The coherence modeled time series is the inverse Fourier transform of cohFFT. The inverse transform produces a 27.31-minute time series of 32,768 values at intervals of 0.05 seconds with frequency resolution to 10 Hz.

- The procedure is straightforward for all additional adjacent nodes displaced horizontally (y-coordinate) and vertically (x)
- A two-step simulation process first simulates an intermediate time series for the vertical component of the separation vector ($dx = (x2-x1)$) and then simulates the required time series for $dy = \text{abs}(y2-y1)$.

The simulation process has been documented for potential ARES-1 users. Test cases have been developed that provide random number input series and simulated time series output for ARES-1 user independent code development and verification.

6. SIMULATION CASE

A simulation case was developed for this paper to illustrate longitudinal component time series at 18.3, 20.3, 35.3, 60.3, 100.3 and 200.3m. The values for the parameters of the PSD model are: $d1=1.35$, $d2=29.035$, $d3=-1.1$, $d4=1.972$, $d5=1$ and $d6=0.845$. The simulation is initiated at 18.3m for $ux=11.42\text{m/s}$ and peak wind speed= 17.21m/s (Eq.2, Anon., 1999). Mean wind speeds (11.65, 13.57, 15.65 and 17.86 and 21.25m/s) at 20.3, 35.3, 60.3, 100.3 and 200.3m elevation are calculated from peak winds at those altitudes (17.55, 19.49, 21.57, 23.76, and 27.08m/s) according to Eqs.1 (for peak wind speed at elevation x, given peak wind at 18.3m) and 2 (for mean wind at x from peak wind at x) in Anon., 1999. The frequency range for the PSD is 1.52588×10^{-4} to 5Hz. Each 109.23 minute time series consists of 65,536 values sampled at 10/s. The coherence functions for the distances between adjacent elevations (2, 15, 25, 40 and 100m) are illustrated in (Fig.3), right to left respectively. The coherence is less than 0.5 for frequencies greater than 0.58, 0.090, 0.058, 0.042 and .020 Hz for $d=2, 15, 25, 40$ and 100m.

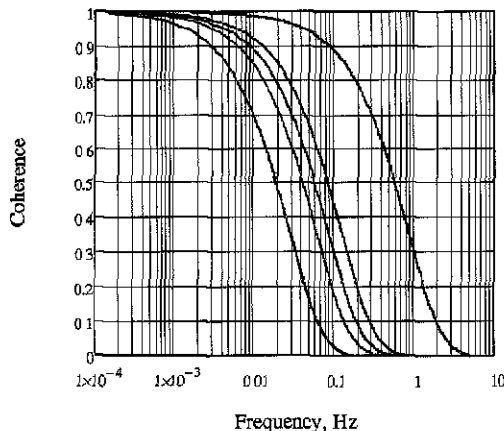


Fig.3 Coherence functions for separation distances of 2, 15, 25, 40 and 100meters, right to left, respectively.

Sixty second segments from six simulated longitudinal

component time series are illustrated in Fig 4; the mean wind speeds at each elevation are added to the longitudinal component. The simulation of the lateral component, not illustrated herein, is by the same process with different constants d1 thru d6 in the PSD model; the means of the lateral component series are zero. If required the simulated wind components can be expressed in another coordinate system appropriate for engineering analysis.

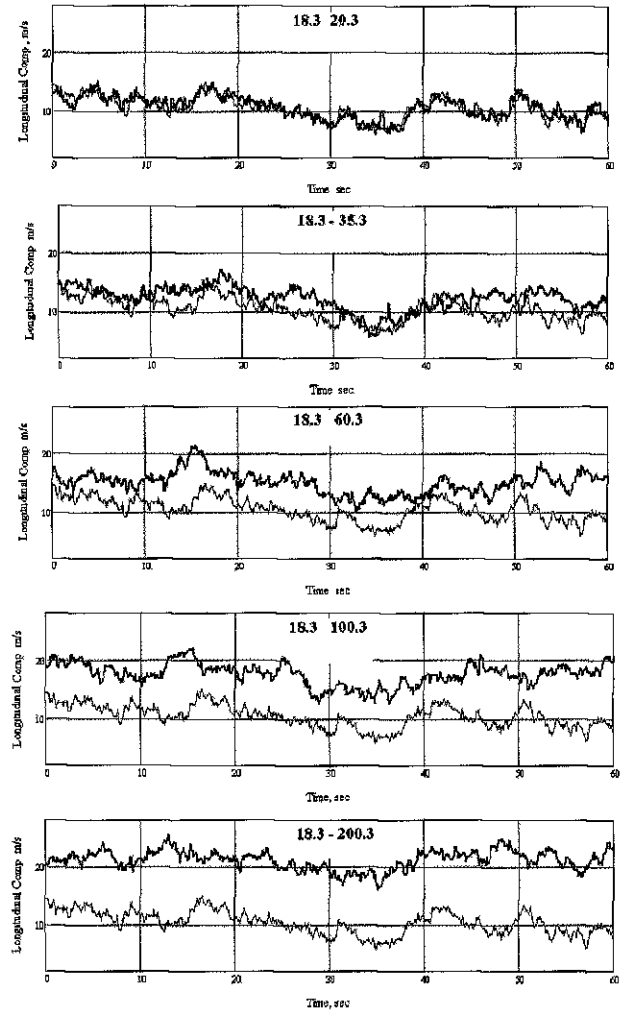


Fig.4 Simulated longitudinal wind component at 18.3m repeated in each panel, and at 20.3, 35.3, 60.3, 100.3 and 200.3m

7. DISCUSSION

A desirable characteristic of the simulation model is that it can be included in a Monte Carlo process that will output a sufficient number of simulations that would mimic the original data used in the derivation of the NASA ground wind model (GWM, Anon., 2000). The GWM was used for calculation of the peak wind and associated mean wind values listed in Sec.6; thus the GWM gust factors (GF, the ratio of peak to mean) are known for comparison to those calculated from multiple outputs of the simulation model. Note that only the mean wind is required in the PSD model of the simulation process. To mimic the process used in the derivation of the GF of the GWM, the GF of the simulation process is defined as the mean of 200 simulations at each of

the six elevations. The GF calculated from the simulation model (dashed upper curve in Fig. 5) with revised values of constants d_1 and d_3 (discussed below) is in good agreement with the GWM values (solid upper curve); the lower curve is based on the original values of constants d_1 and d_3 .

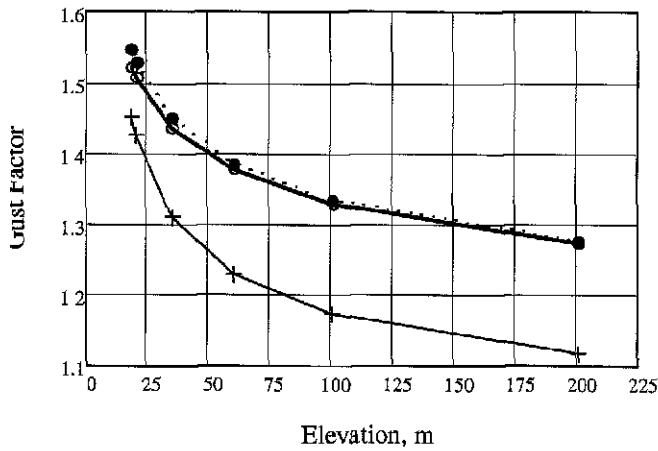


Fig.5 Gust factor as a function of elevation

The gust factors (upper curve in Fig. 5) were obtained with adjusted values of d_1 and d_3 in the PSD model for the longitudinal and d_1 for the lateral component. The published values (Anon., 1999) for d_1 are based on an unrealistic value of the surface roughness parameter z_0 for KSC. Where, z_0 can be "back calculated" using Eq.8 for the longitudinal component or Eq.9 for the lateral component.

$$z_0 = \frac{18.3}{\exp \sqrt{\frac{6.198(0.4)^2}{d_1 * 0.03}}} \quad (8)$$

$$z_0 = \frac{18.3}{\exp \sqrt{\frac{3.954(0.4)^2}{d_1 * 0.1}}} \quad (9)$$

For d_1 equal to 0.807 in Eq.8 or d_1 equal to 0.154 in Eq.9, z_0 is 0.030. A more realistic average value of z_0 equal to 0.13 is closer to but somewhat less than the values in Fichtl and McVehil (1970) yields the values used herein ($d_1=1.35$ for longitudinal and 0.256 for lateral) obtained by solving for d_1 in Eqs.8 and 9.

The constant d_3 for the longitudinal component influences the rate of decrease of GF as a function of elevation. The revision of the published value of d_3 (-1.63, Anon., 1999) is suggested in correspondence from Fichtl (unpublished, 2004) based on a literature search of research studies completed since 1970. Examination of the formulation of Fichtl's 1970 PSD model indicates that d_3 in the simplified but equivalent formulation used herein from Anon.1999 is obtained by multiplication of Fichtl's equation for β by

$(z/18.3)^{-1}$. Thus the variation of gust factor with elevation is described by FZ in Eq.10.

$$FZ = \left(\frac{z}{18.3} \right)^{-0.63-1} \quad (10)$$

Where, d_3 is the exponent (-1.63). Fichtl's recent discussion suggests various choices for increasing the "-.63" value; the value chosen (-0.10) yields the revised value of d_3 (-1.1) that produces good agreement with the rate of decrease in GF predicted with GWM.

8. CONCLUSION

A simulation process has been developed for generation of the longitudinal and lateral components of ground wind atmospheric turbulence as a function of mean wind speed, elevation, temporal frequency range and distance between locations. The distance between locations influences the spectral coherence between the simulated series at adjacent locations. Short distances reduce correlation only at high frequencies; as distances increase correlation is reduced over a wider range of frequencies.

The choice of values for the constants d_1 and d_3 in the PSD model is the subject of work in progress. An improved knowledge of the values for z_0 as a function of wind direction at the ARES-1 launch pads is necessary for definition of d_1 . Results of other studies at other locations may be helpful as summarized in Fichtl's recent correspondence. Ideally, further research is needed based on measurements of ground wind turbulence with high resolution anemometers at a number of altitudes at a new KSC tower located closer to the ARES-1 launch pad. The proposed research would be based on turbulence measurements that may be influenced by surface terrain roughness that may be significantly different from roughness prior to 1970 in Fichtl's measurements. Significant improvements in instrumentation, data storage and processing will greatly enhance the capability to model ground wind profiles and ground wind turbulence.

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